

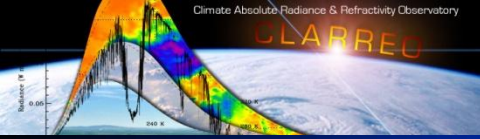
CLARREO Infrared Instrument Suite

CLARREO RO Instrument Suite

CLARREO IR Instrument Team
CLARREO RO Instrument Team

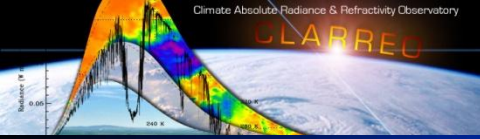
Presenting: Marty Mlynczak

May 17 2011

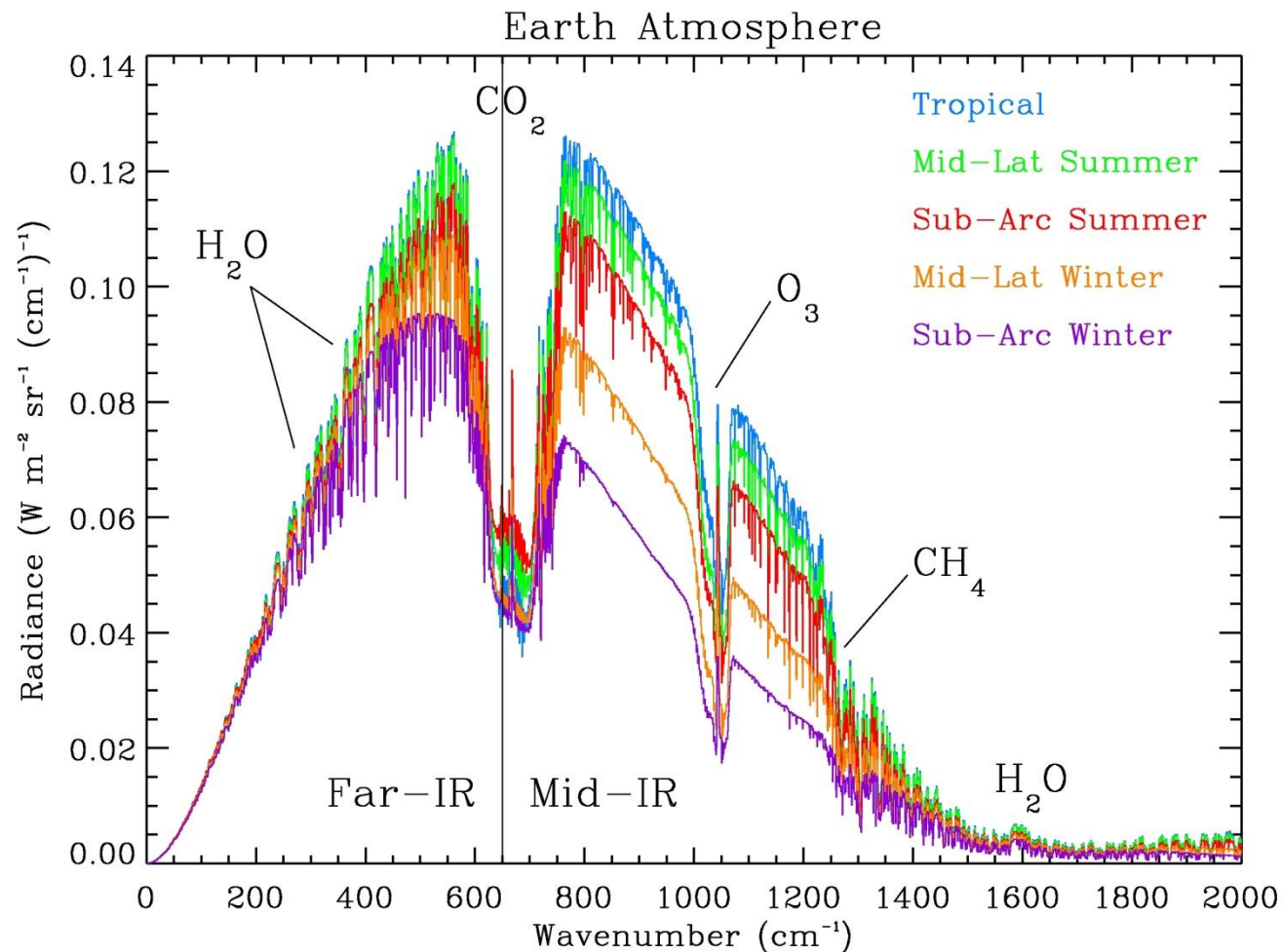


Level 2 IR Instrument Requirements

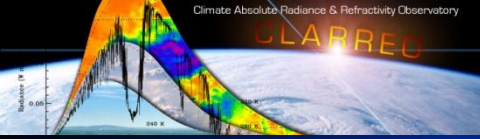
- Spectral Range: 200 to 2000 cm^{-1} (2760 cm^{-1} goal)
 - Rationale:
 - Spectral Range for Climate Benchmark and Fingerprinting
 - Spectral Range for Reference Intercalibration of Longwave Broadband Sensors (CERES; GERB; Megha-Tropiques)
- Spectral Resolution: 0.5 cm^{-1} unapodized
 - Rationale:
 - Ability to resolve effects of temperature and water vapor as functions of altitude
- Systematic Uncertainty: 0.100 Kelvin (coverage factor $k=3$)
 - Rationale:
 - Driven by interannual variability of IR spectra
- IFOV: No less than 25 km
 - Rationale:
 - Enables climate record, reference intercalibration
- Ground Sampling: One calibrated spectrum every 200 km or less
 - Rationale:
 - Nyquist samples the autocorrelation length of the radiation field



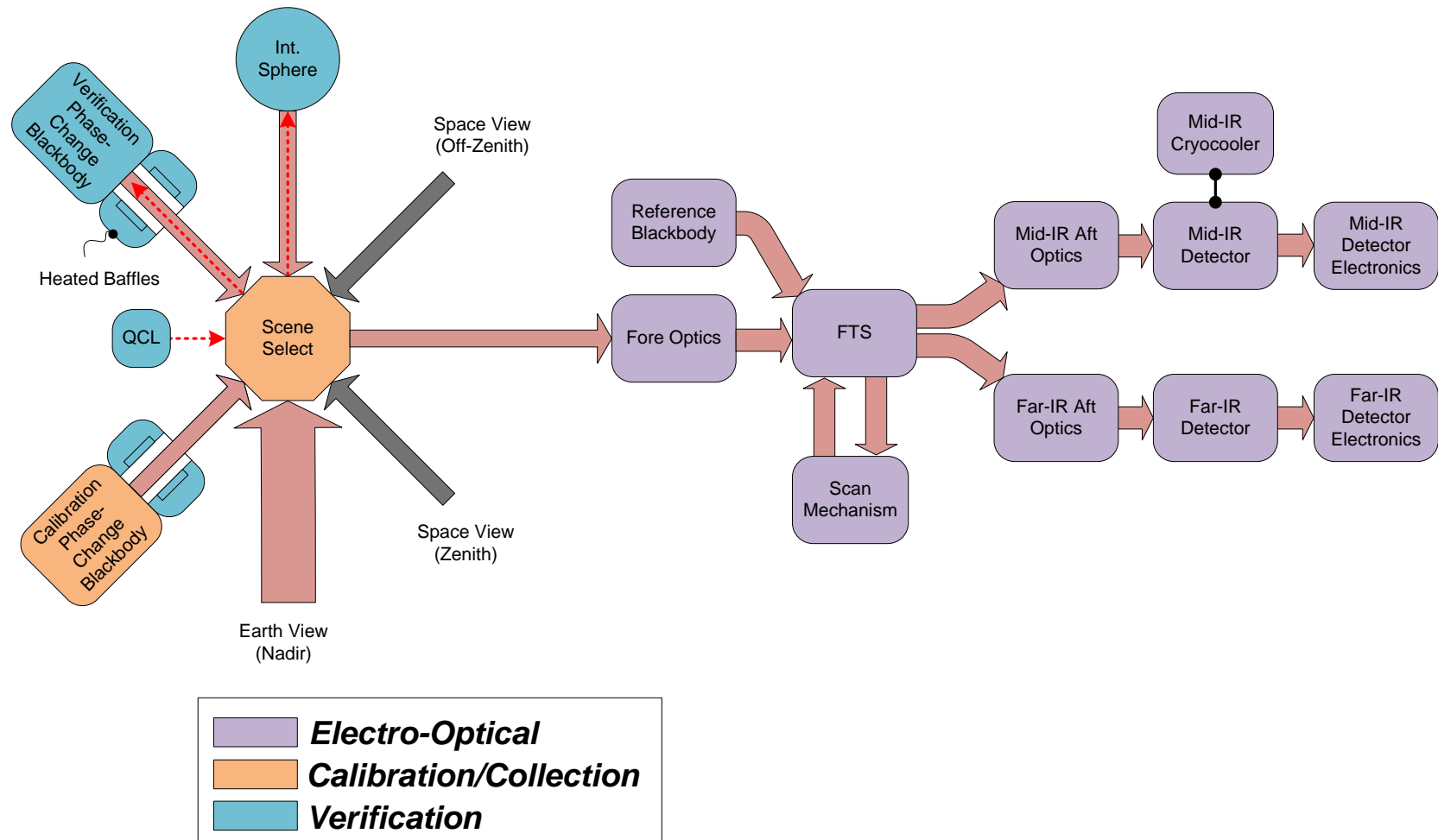
Atmospheric Radiance Spectra



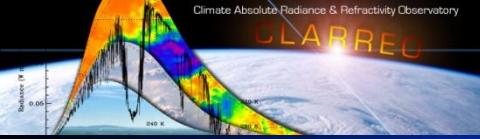
Far-IR and natural variability are significant



IR Concept Consists of Electro-Optical and Calibration-Verification Modules



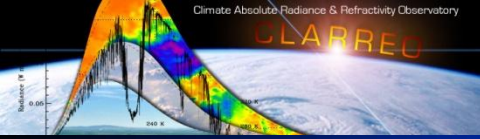
Verification System Enables on-Orbit SI Traceability



Verification System Provides SI Traceability

- Maintaining SI traceability requires quantifying errors and verifying accuracy on orbit
- This requirement is partially met through traditional methods:
 - Frequent views of ambient blackbody and deep space for radiance calibration and estimates of instrument drift
 - Multiple temperature sensors used to detect and correct for changes in offset
 - Detector nonlinearity characterized during preflight calibration
- Requirement fully satisfied by using on-orbit verification system to:
 - Quantify sources of bias that affect calibration accuracy
 - Polarization effects
 - Instrument line shape
 - Verify accuracy through measurements of a known source
 - Variable temperature blackbody that is not used for instrument calibration

SI Traceability: Unbroken chain of comparison with stated uncertainties



On-Orbit Calibration of the Verification BB

SI (Kelvin)-Based IR Radiance Scale Realization

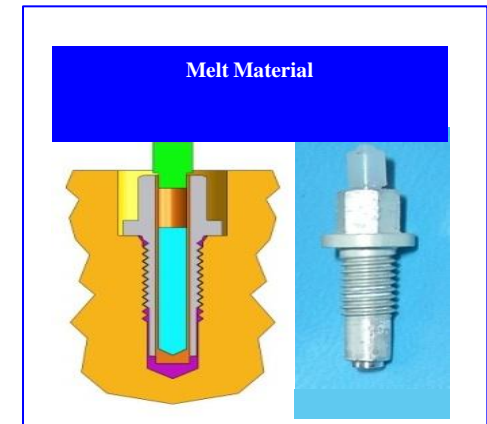
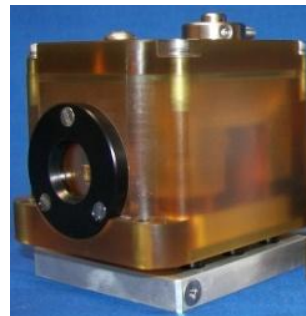
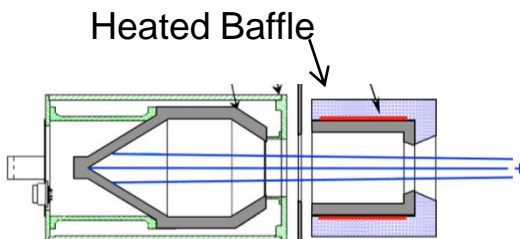
$$L_{BB}(\nu, T_{BB}) = \underbrace{\epsilon_{BB}(\nu)}_{\text{Emissivity}} * \frac{2h\nu^3}{c^2} * \frac{1}{\underbrace{(e^{(h\nu/kT_{BB})} - 1)}}_{\text{Temperature}} \quad \text{Planck Equation}$$

Cavity Emissivity Measurement

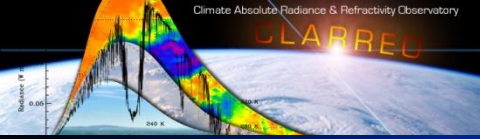
Quantum Cascade Laser (QCL)

3 Phase Change Cells Provide SI Traceable Fixed Points (-40°C, 0°C, 30°C)

Phase Change Cells



On-orbit, SI traceable measurements of temperature and emissivity



Meeting Level 1 Requirements

SI Traceability: Unbroken chain of comparisons with stated uncertainties

Estimated $k=3$
uncertainties at 1000 cm^{-1}
for scene temperature of
250K, with calibration BB
at 270K

Total
Combined
Uncertainty
54 mK

IR Level 1
Requirement
100 mK, $k=3$

Combined Type B
Uncertainty
54 mK

Annual
Type A
Uncertainty
< 1 mK

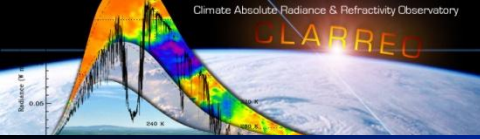
Calibration
Blackbody
Radiance
31 mK

Space View
Radiance
< 1 mK

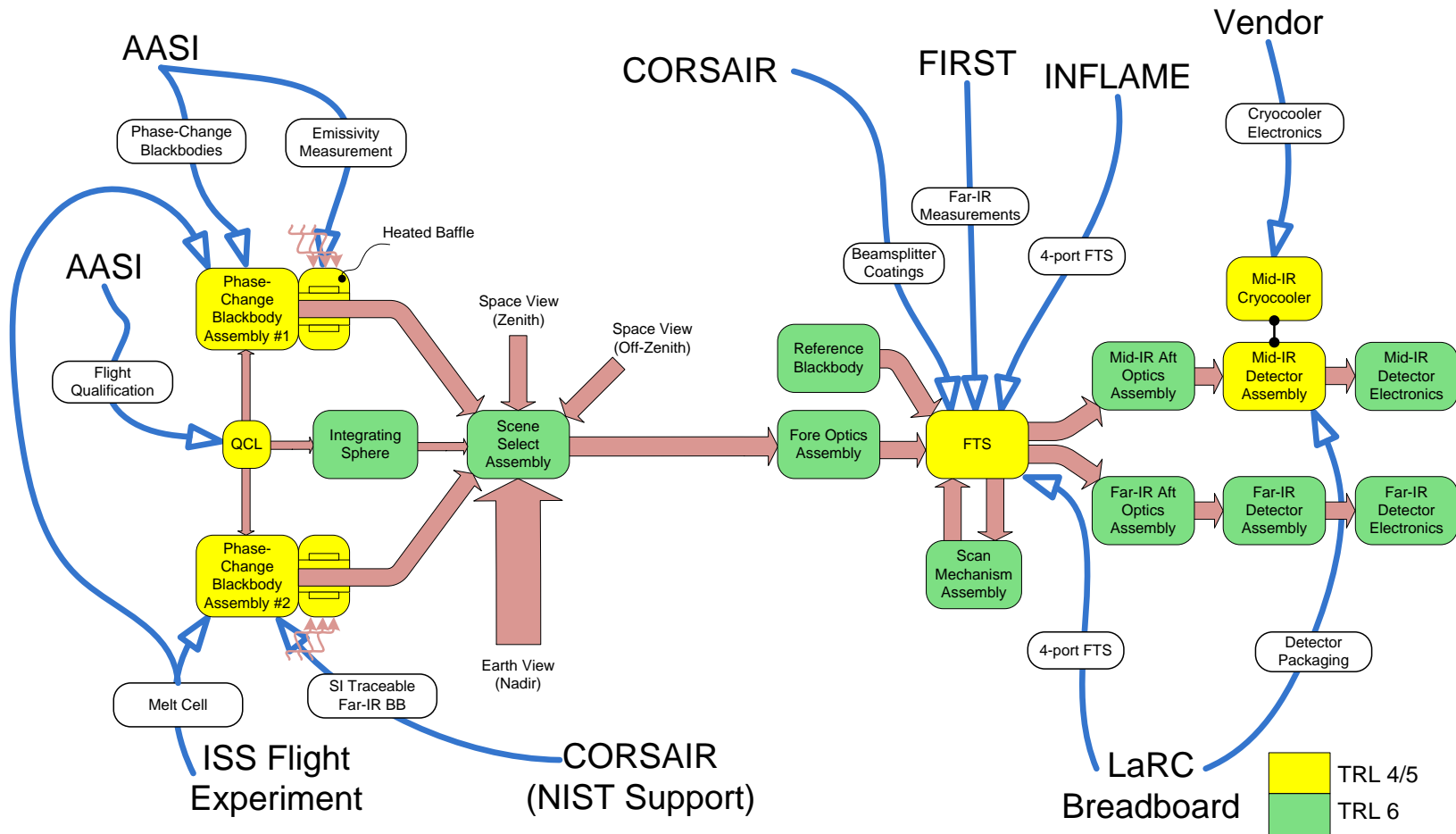
Gain
Nonlinearity
29 mK

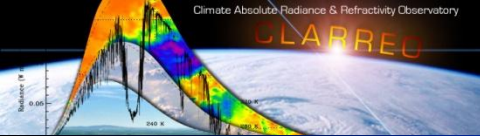
FTS
Uncertainty
Terms
33 mK

Modeling work to date shows ability to meet level 1 & level 2 requirements

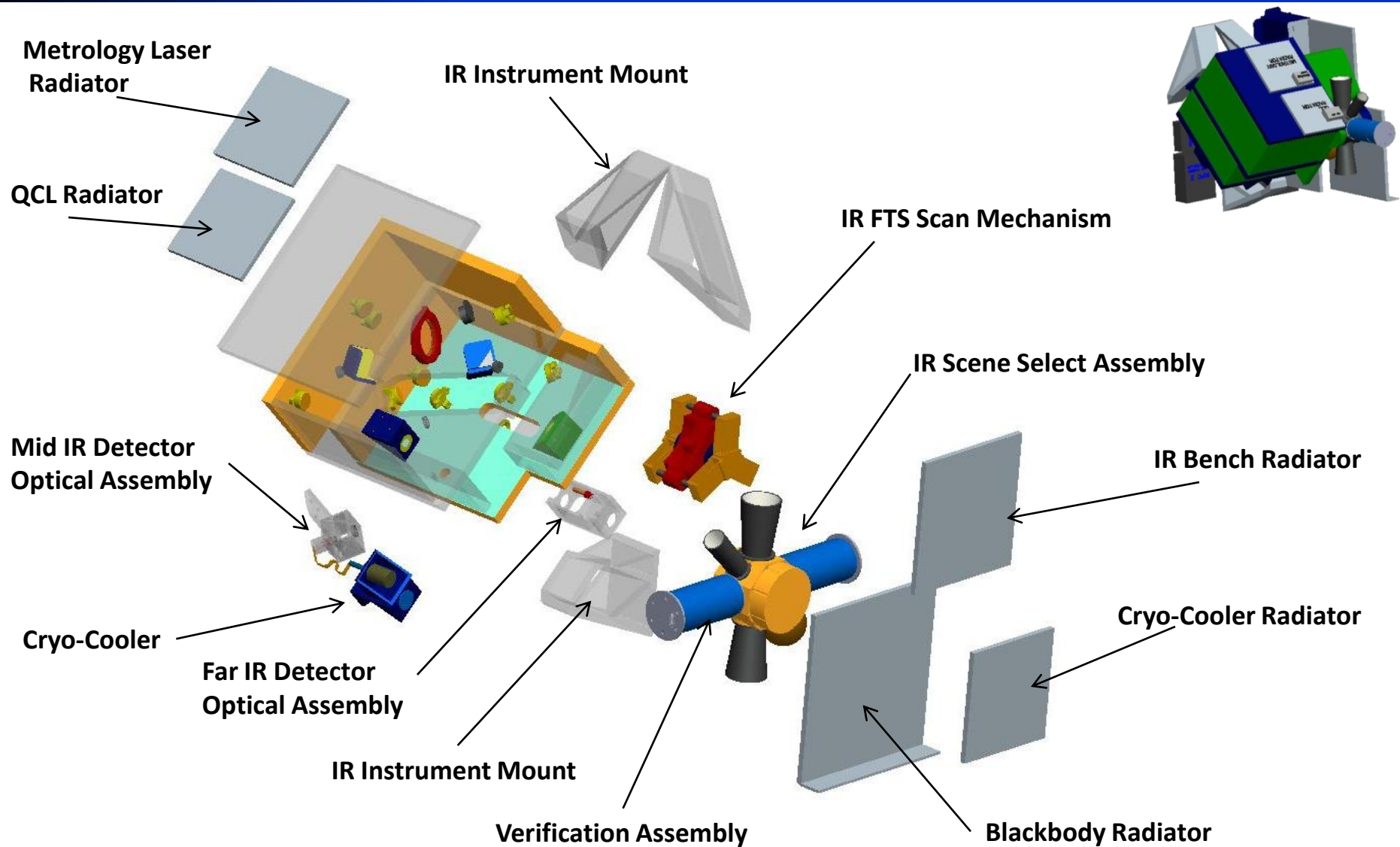


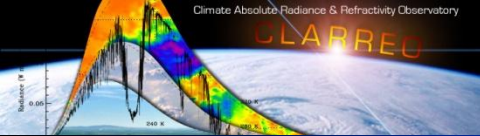
Technology Development Plan Leverages Hardware Matured Through Breadboard and IIP Programs





IR Instrument Suite





Infrared Instrument Comparison

| Class | Instrument | Mass (kg) | Pwr (W) | Vol (m ³) | Spectral Band (μm) | Spectral Rsltn (cm ⁻¹) | Absolute Accuracy (K) | IFOV (km); Swath Width (km) | Detector Format |
|----------|-------------------|-----------|---------|-----------------------|--------------------|------------------------------------|-----------------------|-----------------------------|------------------------------------|
| Explorer | Voyager IRIS | 18 | 14 | | 4-55 | 4.3 | 0.4-1.7 | N/A | Single element |
| | CIRS | 39 | 33 | 0.35 | 7-1000 | 0.5 - 20 | 1.9-6.2 | N/A | 2 FIR detectors; 2 1x10 MIR arrays |
| | ACE | 41 | 37 | 0.17 | 2.3-13.3 | 0.02-1.0 | | Solar occult | Two single-element |
| | CLARREO IR Suite* | 76 | 124 | 0.28 | 5 – 50 | 0.5 | 0.1 K (k=3) | 25 nadir only | Three single-element |
| Sounders | CrIS | 165 | 123 | 0.60 | 4 – 15 | 0.62-2.5 | 0.3 K | 14 +/- 1000 | Three 3x3 arrays |
| | AIRS (Grating) | 177 | 220 | 1.75 | 4 – 15 | 0.5-2.5 | 0.3 K | 13.5 +/- 900 | 2378 element array |
| | IASI | 236 | 210 | 1.71 | 4 – 15 | 0.25 | 0.5 K | 12 +/- 1000 | Three 2x2 arrays |

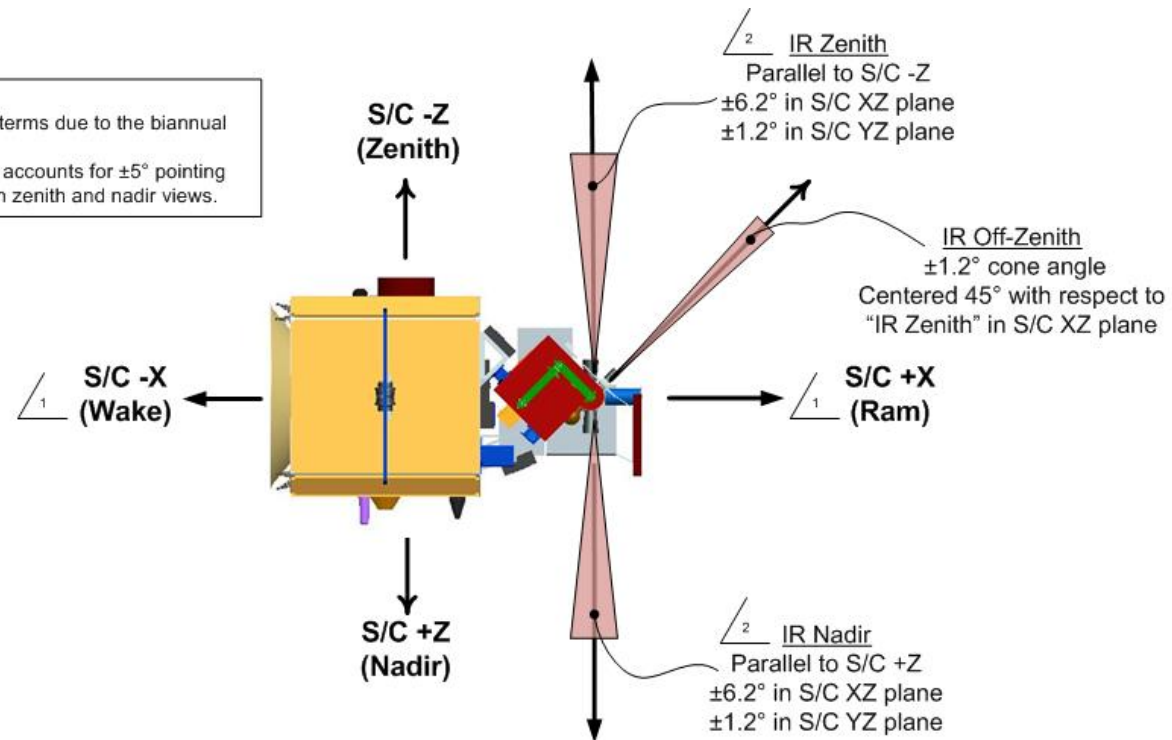
*CLARREO is verified on-orbit to SI standards

IR Suite Accommodations

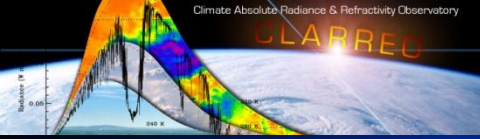
| Mass | Avg. Power | Peak Power | Data Rate | Data Volume |
|-------|------------|------------|------------|-------------|
| 76 kg | 124 W | 233 W | 228 kb/sec | 20 Gb/day |

NOTES:

- (1) "Ram" and "Wake" are relative terms due to the biannual yaw flips.
- (2) "IR Zenith" and "IR Nadir" FOR accounts for $\pm 5^\circ$ pointing needed for motion compensation in zenith and nadir views.

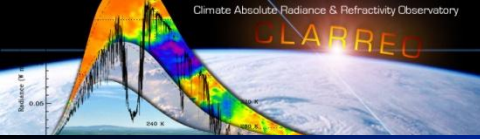


IR Suite Fields-of-Regard



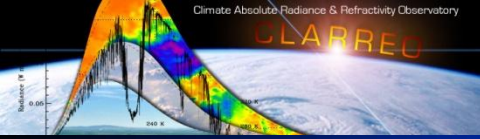
Ongoing Pre-Phase A Activities

- Developing IR Calibration Demonstration System (CDS)
 - Validate instrument model
 - Demonstrate required measurement accuracy
- Technology development
 - Complete IIPs (AASI, CORSAIR)
 - Compare UW Breadboard, CDS (strongly desired; seeking funding)



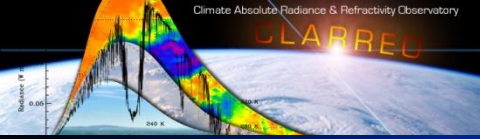
Summary

- IR Instrument Suite Concept meets the science objectives and is feasible
 - Infrared Fourier transform spectrometer
 - Calibration methodology (preflight and on orbit)
 - Verification system
- Instrument design concept is viable
 - Uncertainty budget is defined
 - Key trade studies have been completed
- Plans to continue assessment of calibration systems
 - Complete the IIPs
 - Complete the CDS



GNSS – RO Instrument Summary

Thanks to the TriG Team at JPL for the status update!



GNSS-RO Requirements

Level 1 Science Requirements

Baseline Accurate and Traceable

- Observations shall have their accuracy uncertainty traceable to SI standards

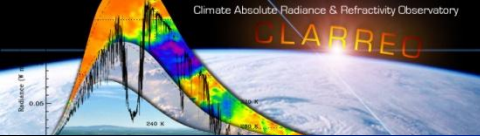
Atmospheric Refractivity Baseline Science Measurement

- Spatial and temporal sampling sufficient to provide global coverage and to reduce sampling biases
- Changes in annual means of refractivity with an uncertainty of 0.03% ($k=1$, over 90% TBR of the zones) for 5-20 km altitude

Draft Level 2 GNSS-RO Measurement Requirements

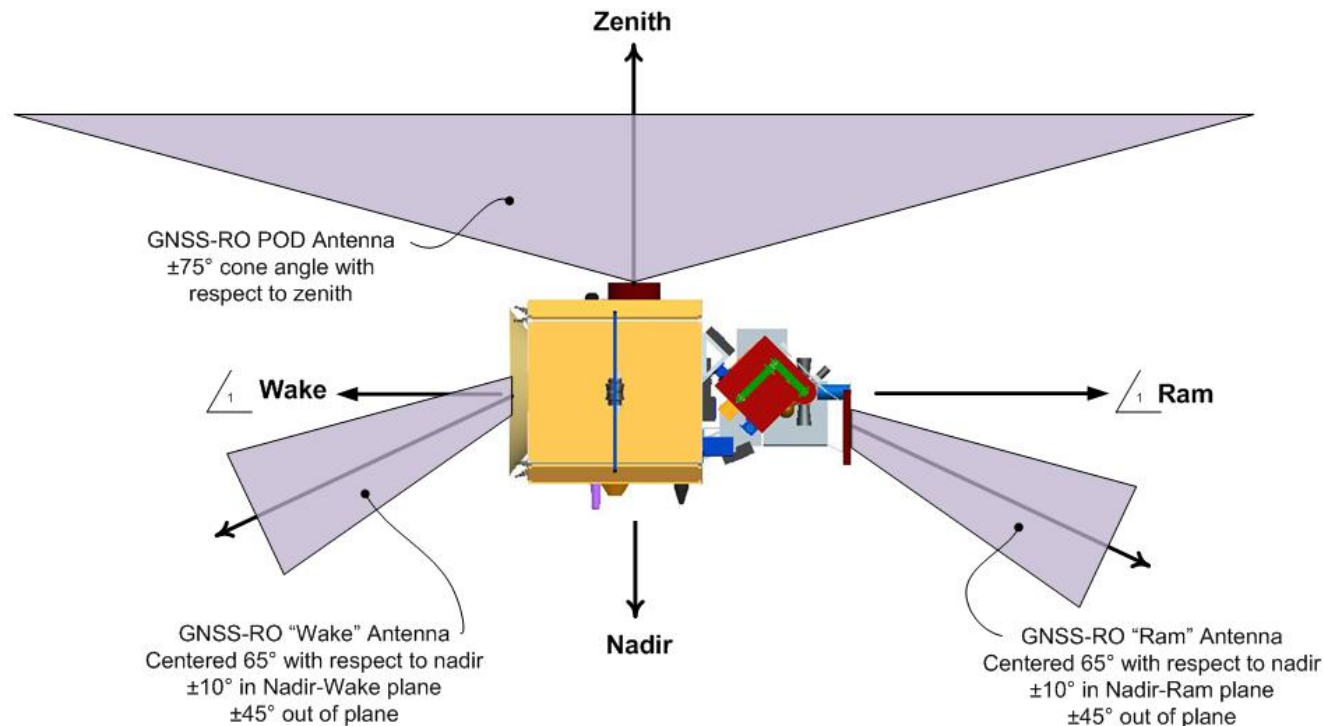
- **Phase Delay Rate Uncertainty: ≤ 0.5 mm/s (from all error sources)**
Required to achieve 0.03% refractivity uncertainty
- **Sampling Density: 1000 occultations/day**
Required to achieve 0.03% refractivity uncertainty

Phase delay rate is directly traceable to the SI standard for time (the second)

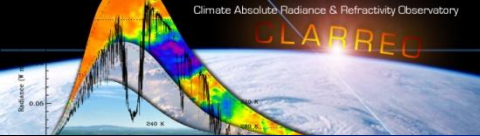


GNSS-RO Instrument Accommodations

| Mass | Avg. Power | Peak Power | Data Rate | Data Volume |
|-------|------------|------------|------------|-------------|
| 18 kg | 35 W | 40 W | 119 kb/sec | 10 Gb/day |



GNSS-RO Antenna Fields-of-View



GNSS-RO Preliminary Error Budget

Troposphere (5-20km)

Testing that requirements are met for this region to be done at 18km.

| Phase rate error (mm/s) | Refractivity error (%) |
|-------------------------|------------------------|
|-------------------------|------------------------|

Measurement Requirement A: Individual Sounding

Systematic

| | | |
|---------------------------------------|-------|---------|
| Retrieval Non-Linearity | 0.000 | 0.0000% |
| RO antenna phase center determination | 0.021 | 0.0007% |
| Atmospheric multipath | 0.000 | 0.0000% |
| Ionospheric residual | 0.300 | 0.0100% |
| LEO POD | 0.054 | 0.0018% |
| Clock accuracy | 0.030 | 0.0010% |
| Attitude knowledge | 0.024 | 0.0008% |
| Attitude rate knowledge | 0.150 | 0.0050% |
| Local multi-path | 0.240 | 0.0080% |
| <i>Total</i> | 0.418 | 0.0139% |

Random

| | | |
|---------------------------|-------|---------|
| Instrument precision | 0.240 | 0.0080% |
| Ionospheric scintillation | 0.060 | 0.0020% |
| Gravity waves | 0.090 | 0.0030% |
| Clock precision | 0.099 | 0.0033% |
| <i>Total</i> | 0.281 | 0.0094% |

Measurement Requirement B: Climatological Averaging

Systematic

| | | |
|---------------|-----|---------|
| Diurnal cycle | n/a | 0.0100% |
| <i>Total</i> | n/a | 0.0100% |

Random

| | | |
|------------------|-----|---------|
| Sampling density | n/a | 0.0220% |
| <i>Total</i> | n/a | 0.0220% |

Total systematic error (target) 0.0170%

Total systematic error 0.0172%

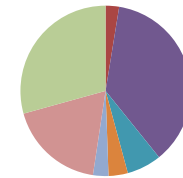
Total random error (target) 0.0250%

Total random error 0.0239%

Total error 0.504 0.0294%

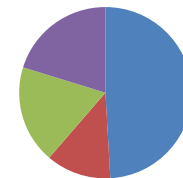
Requirements 0.5 0.03%

Systematic Errors



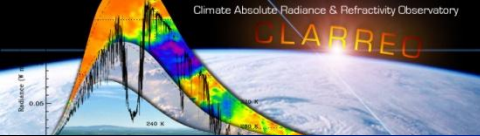
- Retrieval Non-Linearity
- RO antenna phase center determination
- Atmospheric multipath
- Ionospheric residual
- LEO POD
- Clock accuracy
- Attitude knowledge
- Attitude rate knowledge
- Local multi-path

Random Errors



- Instrument precision
- Ionospheric scintillation
- Gravity waves
- Clock precision

Error Budget Successfully Peer Reviewed by RO Community Experts



GNSS-RO Receiver / Processor

JPL TriG Receiver

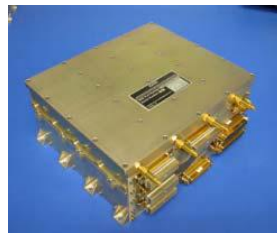
- Currently under development for Decadal Survey and COSMIC-2 missions
- Leverages previous GNSS-RO receivers
 - Provides capability to track signals of future GNSS constellations
 - Has improved radiation hardening
- Development schedule supports CLARREO
 - Engineering Models will be completed six months prior to CLARREO's GNSS-RO Instrument SRR

TriG Compatibility

| CLARREO Requirement | TriG Capability |
|---------------------------|------------------------------|
| Track GPS and Galileo | GPS, Galileo, GLONASS |
| TID ~ 15 kRad | > 40 kRad |
| Sample Rate=100 Hz | Sample Rate=100 Hz |
| Vertical Resolution=200 m | Vertical Resolution=100 m |
| Track 6 POD Satellites | Tracks 10 POD Satellites |
| Track 4 RO Satellites | Tracks up to 6 RO satellites |
| 1553B or RS-422 Interface | RS-422 Interface |



JPL "Blackjack"
CHAMP
GRACE



JPL / Broad Reach "IGOR"
COSMIC



JPL / Broad Reach "IGOR"
TerraSAR-X
TanDEM-X (2010)



JPL / Broad Reach "IGOR+"
KOMPSAT-5 (2010)

CLARREO leverages a long history of flight RO receivers



TriG Developments Since CLARREO MCR

Date: May 13, 2011

Jeff Tien, TriG Delivery Manager
Anthony J. Mannucci, RO Formulation
Jet Propulsion Laboratory, California Institute of Technology

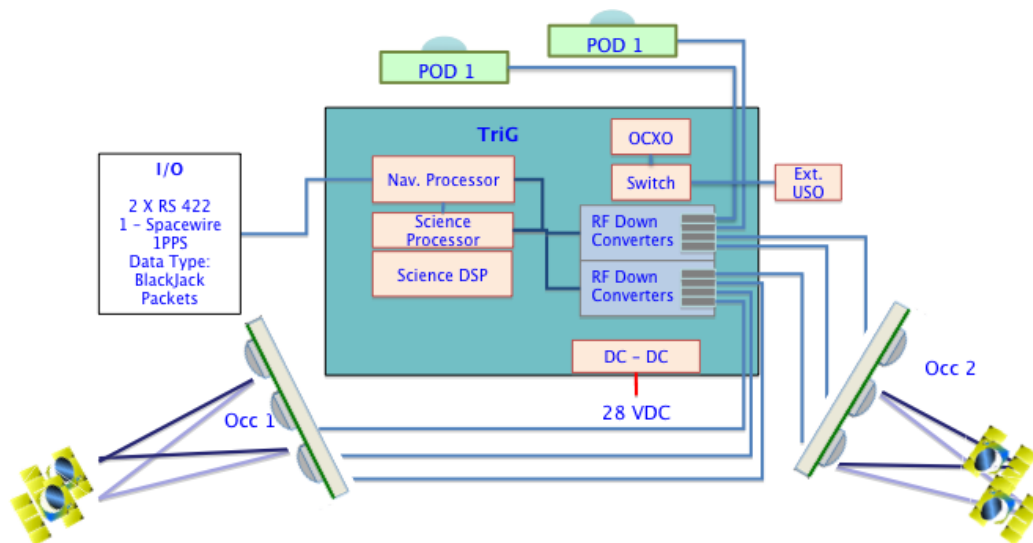


TriG GNSS Receiver

Product: Engineering Model GNSS Science Receiver

Key Applications:

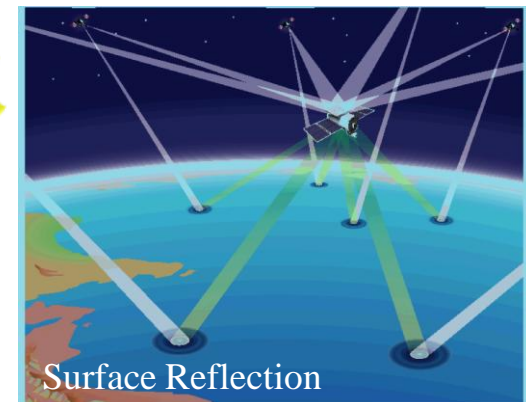
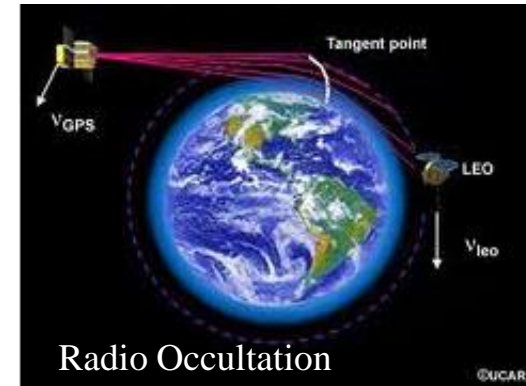
- Radio Occultation (RO)
- Precise Orbit Determination (POD)



- Designed to meet known/expected CLARREO requirements

Customers:

- COSMIC II (NOAA), Grace F/O, ICESat II, SWOT and missions of opportunity

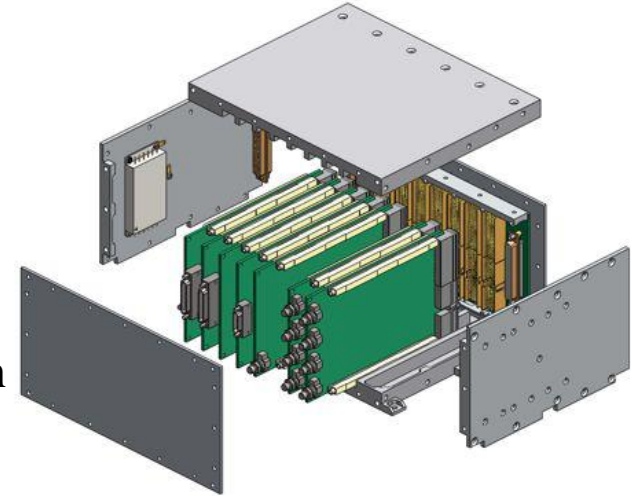


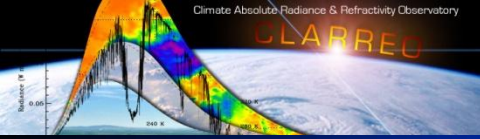


Recent Accomplishments

- Completed Preliminary Design Review (Dec 2011)
 - Key finding: Design is compliant with program requirements
- Completed preliminary design of the TriG EM Hardware
- Currently focusing on completing development in areas with highest technical risk:
 - Navigation and Science Processor Cards
 - RF Downconverter (RFDC) and Clock Distribution Card
- Completed radiation test on key RFIC (radio frequency front-end integrated circuit)
- Industrial partner (BroadReach Engineering) is currently on startup contract

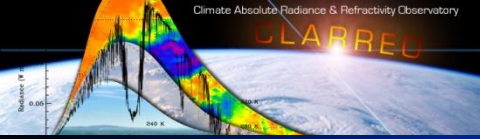
TriG GNSS Receiver



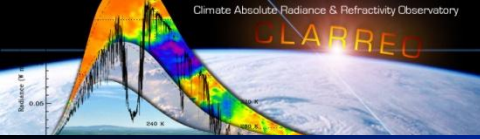


GNSS – RO Summary

- The GNSS-RO instrument concept meets the science requirements
 - Draft Level 2 measurements requirements have been derived
 - Preliminary error budget has guided the instrument design concept
- The GNSS-RO instrument concept is feasible
 - Radio occultation is a mature measurement technique that has been used since 1995 on numerous space missions
 - Technical searches have been conducted to determine the GNSS-RO state-of-the-art and to identify potential instrument suppliers
- GNSS-RO technology development (TriG) is proceeding



Backups



IR Level 1 Requirements

- **Accurate and Traceable:**
 - CLARREO shall make observations with verifiable on-orbit accuracy sufficient to resolve decadal change and to survive gaps in data sets;
 - Observations shall have their calibration traceable to SI standards in order to allow comparison with future measurements even if data gaps occur.
- **Infrared Science Measurement:** CLARREO shall obtain infrared radiance spectra of the Earth using nadir views from orbiting satellites. Establishing a climate benchmark and providing a reference for satellite intercalibration requires:
 - Broad spectral coverage of the earth emitted spectrum to quantify trends in climate state variables including temperature, atmospheric structure, composition, clouds, and surface properties;
 - Spectral resolution sufficient to resolve contributions from individual greenhouse gas species and to provide vertical structure information;
 - Radiance measurement bias that corresponds to < 0.1 K uncertainty in brightness temperature ($k=3$) for the range of expected earth scene temperatures and wavelengths relevant to climate.